U.S. Department of Energy
Office of Nuclear Energy, Science and Technology
Advanced Fuel Cycle Initiative (AFCI)
Comparison Report, FY 2003

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Advanced Fuel Cycle Initiative (AFCI) Comparison Report
FY 2003

Language in the Conference Report 108-10 accompanying the Fiscal Year (FY) 2003 Energy and Water Development Appropriations Act requires the Department to submit to Congress each year a report that will provide qualitative and quantitative information to enable Congress to compare the various technology approaches to managing commercial spent fuel (Appendix A). This is the required report for FY 2003.

The repository site at Yucca Mountain, Nevada, could accommodate all the U.S. commercial spent nuclear fuel that has been or will be generated by the current fleet of U.S. nuclear reactors. Should, however, a significant number of new nuclear plants be built in the future, the United States will need either to construct a follow-on repository to address the additional wastes from new nuclear plants or begin advanced treatment of spent fuel to reduce the volume and toxicity of nuclear waste. This report compares various technology options for dealing with the spent fuel generated under an assumed expansion of nuclear power in the United States.

The report comprises two matrices:

- Matrix 1: ***Per Annum* Comparison of Spent Fuel Management Alternatives** (Figure 1); and
- Matrix 2: **Comparison of Advanced Fuel Cycles, Including Thorium** (Figure 2).

<u>Comparison Matrix 1</u>

Matrix 1 provides a picture of the alternative technologies for spent fuel management. Five technologies – Plutonium Extraction (PUREX), Uranium Extraction Plus (UREX+), the hybrid Uranium Extraction/Pyrochemical (UREX/PYRO), the entirely pyrochemical (PYROX), and the Actinide Crystallization (ACP) processes – are compared against the direct disposal of spent fuel (the baseline case).

UREX+ technology supports short-term Advanced Fuel Cycle Initiative (AFCI) objectives. These objectives (as discussed in the January 2003 *Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research*) are, among other things, aimed at separating uranium and possibly minor actinides from spent nuclear fuel. Such separations could benefit the geologic repository at Yucca Mountain and also recover some of the energy remaining in the spent fuel by allowing it to be recycled in existing light water reactors (LWRs). (In the case of the Very High Temperature Reactor, such recycle is unlikely because of the high burnup of its fuel, but this will be investigated further as research and development (R&D) progresses.) UREX/PYRO, PYROX and ACP support longer-term AFCI objectives, which aim at developing material from spent nuclear fuel that could be burned in a future generation of fast spectrum Generation IV reactors that may be commercially deployed around 2040 (*e.g.,* the Gas-Cooled Fast Reactor, the Sodium-Cooled Fast Reactor, the and the Lead-Cooled Fast Reactor). For the purposes of comparison, this analysis assumes that all spent fuel treated is generated by LWRs. While the United States has no interest in pursuing conventional reprocessing[1], we have also included PUREX technology, which results in the separation of pure plutonium, in Matrix 1 for comparison purposes.

<u>Comparison Matrix 2</u>

Matrix 2 compares advanced fuel cycles and includes consideration of thorium-uranium and thorium-plutonium fuel cycles. Transmutation systems and thorium fuel cycles are compared against the once-through (direct disposal) baseline in the areas of utilization of natural resources, high-level waste volume, short term heat load, long term heat load, radiotoxicity and dose, fuel cycle facilities requirements and R&D to attain maturity.

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[1]The May 2001 *National Energy Policy* specifically states on pages 5-17 and 5-22 that “the United States will continue to discourage the accumulation of separated plutonium, worldwide.”

Figure 1 -- Matrix 1
***Per Annum* Comparison of Spent Fuel Management Alternatives**

	Baseline Once-Through LWR	PUREX[1]	UREX+	UREX/PYRO (hybrid process)	PYROX (all pyrochemical)	Advanced Aqueous Process with ACP/UREX+[2]
Annual Input of Spent Nuclear Fuel (Mt)[3]	2,000	2,000	2,000	2,000	2,000	2,000
Annual Net Chemical Consumption (Mt)	-0-	4.2 Mt reagents[4]; 420 Mt glass frit	7 Mt reagents[4]; 124 Mt glass frit	5.6 Mt reagents[4]; 280 Mt zeolite + glass; 42 Mt salt	420 Mt zeolite + glass; 80 Mt salt	0.8 Mt reagents[4]; 124 Mt glass frit
Annual Output: Useable Product						
• Recycle to LWRs[5]	-0-	17 Mt Pu	18 Mt Pu/Np	21.2 Mt Pu/Np/Am/Cm[6]	21.2 Mt Pu/Np/Am/Cm[6]	18 Mt Pu/Np
• Recycle to future reactors	-0-	-0-	3.2 Mt minor actinides	21.2 Mt TRUs	21.2 Mt TRUs; 172 Mt U	3.2 Mt minor actinides
Annual Output: Waste						
• High-level waste	2,000 Mt spent nuclear fuel	490 Mt glass logs; 1,890 Mt U[7]	232 Mt glass logs[8]	280 Mt ceramic waste form	490 Mt ceramic waste form	232 Mt glass logs[8]
• Low-level waste	-0-	350 Mt LLW[9]; 660 Mt cladding	1,892 Mt U; 660 Mt cladding	1,892 Mt U; 660 Mt cladding	1,720 Mt U; 660 Mt cladding	1,892 Mt U; 660 Mt cladding
• Secondary waste[10]	42 Mt	2.12 Mt	3.52 Mt	4.2 Mt	2.12 Mt	1.4 Mt
Energy Utilization Factor[11]	1X	N/A	N/A	N/A	N/A	N/A
• Recycle to LWRs	None	1.3X[11]	1.3X[11]	1.3X[11]	1.3X[11]	1.3X[11]
Proliferation Resistance ("More/Less" references are relative to the Baseline)	Material is Self-Protecting for First 100 yrs[12]; Self-Protection Declines Significantly Thereafter	Less Proliferation Resistant. Produces Direct Plutonium Stream	More Proliferation Resistant. Neptunium Mixed with Plutonium Makes Material Unattractive for Weapons Use	More Proliferation Resistant. Actinides Mixed with Plutonium Makes Material Unattractive for Weapons Use	More Proliferation Resistant. Actinides Mixed with Plutonium Makes Material Unattractive for Weapons Use	More Proliferation Resistant. Actinides Mixed with Plutonium Makes Material Unattractive for Weapons Use ; Requires Less Expensive Facilities than Other Technologies
Technical Maturity Level	Approaching Licensing Phase	In Commercial Operation in Europe	In Final Phase of Laboratory Scale Demonstration	UREX Demonstrated at Lab Scale; PYRO Demonstrated at Engineering Scale	Lab Scale Oxide Reduction Research in Progress; PYRO Demonstrated at Engineering Scale	Researched for Only One Year; ACP demonstrated at Lab Scale for Uranium Step Only[13]
Facilities (number and type) in Addition to Yucca Mountain Repository	Second Repository	One Reprocessing Plant @ 2,000 Mt per year; One Fuel Fab. Plant	One Advanced Fuel Treatment Plant @ 2,000 Mt per year; One Fuel Fab. Plant	One Advanced Fuel Treatment Plant @ 2,000 Mt per year; One Fuel Fab. Plant	Electrorefiner; One Fuel Fab. Plant	One Advanced Fuel Treatment Plant @ 2,000 Mt per year; One Fuel Fab. Plant
Facility Life Cycle Cost, including Credits and D&D, in Addition to Yucca Mountain Repository (millions), Based on 25 Years of Operation						
• Est. RD&D Cost	$4,000[14]	$0	$2,000	$3,000[15]	$3,000[15]	$2,500[16]
• Capital Costs for Advanced Fuel Treatment Plant	$0	$8,000[17]	$6,000	$6,000	$7,000	$4,000
• Capital Costs for Fuel Fab Plant	$0	$2,000	$2,000	$3,000	$3,000	$2,000
• Costs for Second Repository	$46,000	$0	$0	$0	$0	$0
• Operating	$0	$20,000[18]	$14,000[19]	$12,500	$14,000	$12,500
• Storage and Disposal of Uranium	$0	$1,000	$1,000	$1,000	$1,000	$1,000
• D&D	$0	$3,000	$2,400	$2,700	$3,000	$1,800
• LWR Fuel Sale Credits	$0	$12,000	$12,000	$12,000	$12,000	$12,000
Total Life Cycle Cost ($M)	**$50,000**	**$22,000**	**$15,400**	**$16,200**	**$19,000**	**$11,800**
Total Life Cycle Cost Recovery Rate (mills/kWh)	**2.5 m/kWh**	**1.1 m/kWh**	**0.8 m/kWh**	**0.9 m/kWh**	**1.0 m/kWh**	**0.6 m/kWh**
Series One YM Cost Savings	$0	$5,000	$5,000	$5,000	$5,000	$5,000
Avoided Second Repository	$0	$50,000	$50,000	$50,000	$50,000	$50,000
Cost Savings Over Base Case	**$0**	**$33,000**	**$39,600**	**$38,800**	**$36,000**	**$43,200**
Benefits	Does not require development of new technologies; Spent fuel is self-protecting for first 100 years[12]	Extensive commercial experience, proven process	No separation of pure plutonium; No liquid waste streams; solid wastes can be disposed with high packing density due to very low heat load, effectively increasing the capacity of Yucca Mountain	No separation of individual transuranic elements	No separation of individual transuranic elements	Improved version of UREX+ process, with all attendant benefits plus lower cost
Disadvantages	Inefficient use of energy resource; large amounts of nuclear waste; Requires second repository	Separates pure plutonium; Creates large liquid waste volume	Smaller facility relative to PUREX that could make detection of unauthorized activities more difficult	Pyroprocess does not separate Cs-Sr, which are primary source of short-term heat load	Pyroprocess does not separate Cs-Sr, which are primary source of short-term heat load	Relative inexpensiveness and small size of process and facilities could make detection of unauthorized activities more difficult

Figure 1 -- Matrix 1

Per Annum Comparison of Spent Fuel Management Alternatives

Notes

[1]The PUREX estimates in this table are provided for comparison purposes only; this process is not being considered in AFCI planning.

[2]Actinide Crystallization Process

[3]Assumes addition of nuclear generating capacity.

[4]Reagents are substances that take part in other reactions. An example in the case of separations would be the nitric acid in which the separation occurs.

[5]Assumes a fuel burnup rate of 50,000 megawatt-days per metric ton

[6]Material that could be recycled in a tight lattice thermal reactor (e.g., a Reduced-Moderation LWR)

[7]Uranium is shown as high-level waste under the PUREX process because of the presence of technetium.

[8]This waste form may not be borosilicate glass; less expensive waste forms are being developed to take advantage of the very low heat load presented by the wastes from this process. For purposes of comparison, however, a 30% waste loading in glass was assumed here.

[9]This LLW primarily comprises raffinates and other process materials.

[10]Primarily used/broken equipment in the case of spent fuel treatment processes; contaminated resins from shipping cask decon for the once-through case.

[11]1X=Energy From Once-Through Fuel Cycle; nX=Additional Energy Recovered from Spent Fuel Using Alternative Fuel Cycles

[12]100 years represents the time required for the natural decay of isotopes that generate gamma radiation.

[13]R&D Initiated at LANL in FY 2003; Preliminary results very promising.

[14]Based on estimated 33% savings over first repository R&D costs ($6B).

[15]Assumes approximately $1 billion for development and demonstration costs related to licensing tight lattice thermal reactor (see Note 6)

[16]Despite ACP's early stage of development, estimated R&D costs are proportionately less than for other technologies because of the relatively small size of an ACP plant's footprint and the correspondingly less expensive engineering scale demonstration required.

[17]PUREX plants are more expensive to build and operate than advanced treatment plants due to process design and instrumentation improvements in the advanced plants.

[18]PUREX operating costs have been in the range of $400 to $450 per kilogram of material treated.

[19]UREX+ operating costs are estimated to be in the range of $280 per kilogram of material treated.

Figure 2 -- Matrix 2
Comparison of Advanced Fuel Cycles Including Thorium

Fuel Cycle	Description	Criteria: Utilization Of Natural Resources	High-Level Waste Volume	Short Term Heat Load	Long Term Heat Load	Radiotoxicity And Dose	Fuel Cycle Facilities Requirements	R&D To Attain Maturity	Life-Cycle Cost
Once-Through (Direct Disposal)									
Light Water Reactors	Existing fuel cycle with geological disposal	Uses only energy in U235 and fraction of Pu produced in situ	No reduction through recycle/transmutation	Short lived elements remain in spent fuel	Actinides remain in spent fuel	Actinides remain in spent fuel	No fuel cycle facilities	None needed	Low cost is demonstrated
Transmutation Systems									
Light Water Reactors-MOX	Limited multi-recycle of Pu in LWRs (maximum of two)	Uses energy contained in Pu from spent fuel	Recycle and partial transmutation reduces Pu inventories	Heat load is not reduced, but dominant short-lived elements can be partitioned into a separated product to be managed separately	Actinides remain in spent fuel or in special waste forms	Actinides remain in spent fuel or in special waste forms	Need single type of fuel cycle facility and fuel fabrication plant	Need only to develop licensing case	Cost of Electricity is 5% percent higher than once through; but other costs are reduced
Fast-spectrum Reactors	Closed Cycle with Multi-recycle of TRU's	Uses all energy in spent fuel. Potential for using some or all energy in natural U238 -- up to 60x (see Matrix 1, Note 11)	Recycle and transmutation reduces mass of Heavy Metals by ~ 100 and volume of HLW by ~ 5 to 6	Heat load is not reduced, but dominant short-lived elements are partitioned into a separated product to be managed separately	Actinides are destroyed, eliminating long-term heat load	80 percent of the actinides are destroyed, significantly reducing toxicity	Need single type of fuel cycle facility and fuel fabrication plant	Significant R&D required for commercial deployment.	Information Not Available
Accelerator-Driven Systems	Closed Cycle with Multi-recycle of TRUs -- Provides total destruction of actinides	Uses all energy in spent fuel. Electricity production may be limited.	Recycle and transmutation reduces mass of Heavy Metals by ~ 100 and volume of HLW by ~ 5 to 6	Heat load is not reduced, but dominant short-lived elements are partitioned into a separated product to be managed separately	Actinides are destroyed, eliminating long-term heat load	99 percent of the actinides are destroyed, significantly reducing toxicity	Need single type of fuel cycle facility and fuel fabrication plant	Significant R&D required for both reactor and coupling of accelerator	Information Not Available
Thorium Fuel Cycles									
Light Water Reactors - Open Thorium Cycles	Heterogeneous or homogeneous U-Th assemblies in standard LWR's	Makes use of thorium resources, which are abundant.	HLW volume comparable to once-through LWR.	Short lived elements remain in spent fuel.	Heat load is reduced from uranium cycle -- no americium produced.	Radiotoxicity is reduced from uranium cycle -- no americium produced.	May need new fuel fabrication facilities	Requires development of new fuel technology -- extensive testing required	Information Not Available
High-Temperature Gas-Cooled Reactors - Open Thorium Cycles	Uses U-235 and thorium-based fuel technology.	Makes use of thorium resources, which are abundant.	Minimum waste volume because of high burnup capability.	Short lived elements remain in spent fuel.	Heat load is reduced from uranium cycle -- no americium produced.	Radiotoxicity is reduced from uranium cycle -- no americium produced.	New fuel fabrication facilities required.	Requires development of new fuel technology -- extensive testing required	Information Not Available
High-Temperature Gas-Cooled Reactors - Thorium-Plutonium Recycle	Thorium-plutonium fuel cycle provides for efficient destruction of plutonium, however, U-233, a fissile material, is produced.	Energy in Pu produces U-233 which, if recycled, provides for a 1.3X fuel utilization (see matrix 1 for definition of fuel utilization)	Minimum waste volume because of high burnup capability can be improved further with recycle, however recycle most likely would be very expensive	Short lived elements from LWR fuel are partitioned into a separated product to be managed separately; short lived elements produced in the HGTR remain in spent fuel unless separations technology is used -- this most likely will be very expensive because of remote handling and shielding requirements.	Actinides remain in spent fuel or need to be incorporated in special waste forms, or treated to be used in fast-spectrum reactors	Actinides remain in spent fuel or need to be incorporated in special waste forms	New fuel fabrication facility required	Significant R&D required for thorium-plutonium fuel development and treatment technologies	Information Not Available

Appendix A

Language Accompanying the Fiscal Year 2003 Appropriation

Excerpt from House Report 108-10

"*Advanced Fuel Cycle Initiative.*...

"...In order to ensure that the Department's AFCI can lead to useful and practical technologies, the Office of Nuclear Energy, Science and Technology is directed to provide Congress with an annual AFCI Comparison Report. The report will provide qualitative and quantitative information to enable Congress to compare the various technology approaches to managing commercial spent fuel. The first such report is due by May 30, 2003, and should be updated each year thereafter so long as the Department continues its AFCI research activity. This report should include comparison matrices that contrast the advantages and disadvantages of possible fuel treatment and advanced fuel cycle technologies. The technologies should be evaluated with respect to energy and chemical inputs, product and waste stream outputs, proliferation considerations, estimated R&D and facility life cycle costs (i.e., capital, operating, and D&D plus disposal of wastes), and the estimated number and type of facilities required. If the Department cannot provide specific, quantitative information (such as for yet-to-be developed technologies), it should identify in the matrices the estimated dates by which ongoing R&D will provide the answers. Today's commercial light water reactor fuel cycle and spent nuclear fuel disposition should be used as the basis for comparison and to bound and define performance objectives for the new technologies.

"One matrix should compare spent fuel treatment technologies, comparing advanced fast reactor systems, accelerator systems, and other existing and proposed reprocessing and transmutation technologies (e.g., PUREX, UREX, UREX+) against the current once-through approach with spent fuel from light water reactors. The second matrix should include a similar contrast of the advantages and disadvantages and facility requirements for advanced fuel cycles, and should specifically address the six innovative reactor concepts that the member countries of the Generation IV International forum have agreed to pursue. The second fuel cycle matrix should also include consideration of thorium-uranium and thorium-plutonium fuel cycles and the gas turbine modular helium reactor...."